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THE EFFECTS OF INTEGRATING STEM DESIGN THINKING INTO EDUCATION FOR SUSTAINABLE DEVELOPMENT ON STUDENTS' SCIENTIFIC MODELING SKILLS

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Abstract. *Scientific modeling is a fundamental tool in STEM education that facilitates the understanding and explanation of complex phenomena. This study examines the effects of the STEM Modelling Design Thinking (STEM MDT) compared to the STEM Project Based Learning (STEM PjBL), particularly in the context of Education for Sustainable Development (ESD), in enhancing students' scientific modeling skills. Using a quasi-experimental design with non-equivalent pre-test and post-test control groups, the study involved 108 ninth-grade students in the experimental group (55 students) who participated in the STEM MDT, while the control group (53 students) engaged in STEM PjBL. Data were collected by evaluating scientific modeling skills before and after the intervention. The results indicated that the STEM MDT significantly improved students' scientific modeling skills, with effect sizes ranging from moderate to very large (Cohen's d = .91), compared to moderate improvement (Cohen's d = .43). These findings suggest that integrating ESD within the STEM MDT framework not only enhances scientific modeling competencies but also equips students to address complex real-world challenges. This study highlights the potential of STEM MDT as an innovative pedagogical approach for educators and policymakers seeking to cultivate essential skills in future generations.*

Keywords: *scientific modeling, STEM education, design thinking, education for sustainable development, project based learning*

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Introduction

To address the demands of 21st-century education, adopting creative instructional strategies that are seamlessly incorporated into the teaching process is crucial for developing learners with global competencies, particularly through the application of the Science, Technology, Engineering, and Mathematics (STEM) framework. The STEM approach integrates multiple disciplines to strengthen students' grasp and mastery of key foundational knowledge, as well as cultivating skills necessary for the 21st century (Akcan et al., 2023; Wan et al., 2021). The skill of interpreting concepts in science education through STEM is supported by skills in scientific modeling, where the development of scientific models represents something that may be too small to see or too large to imagine, for example, the Bohr model of the atom (Schwarz et al., 2009). One of the primary tools in STEM education is scientific modeling, which helps students understand and explain complex phenomena (Bielik et al., 2018; Schwarz et al., 2009b; Van Driel & Verloop, 2002). The significance of this research lies in its contribution to addressing global challenges through science education by linking students' modeling competencies with real-world problems, particularly those related to climate change. Although much attention has been paid to SDG 4 (Quality Education), this study extends its relevance to SDG 13 (Climate Action) by integrating Education for Sustainable Development (ESD) into STEM learning. The STEM approach facilitates interdisciplinary learning that empowers students not only to understand abstract scientific concepts through modeling but also to apply that understanding in meaningful ways, such as designing context-based projects that offer solutions to environmental problems around them (Sutaphan & Yuenyong, 2023). This approach makes science education more relevant, action-oriented, and impactful across different generations. In this way, scientific modeling serves not only as a cognitive bridge to support conceptual understanding but also as a core competency to enable students to become problem solvers and active agents of change in their local and global communities (Krell & Krüger, 2016). Through modelling, students learn to identify relevant variables, understand the relationships between the components within a system, and make predictions based on the models they create (Krell et al., 2019; Krell & Krüger, 2016). This method corresponds

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to the primary goals of STEM education, which emphasize the development of competencies such as working collaboratively, communicating clearly, and addressing problems effectively (Baran et al., 2021).

A scientific model is a simplified and abstract representation of a system or set of phenomena that effectively illustrates its main attributes, and can be utilized to create explanations and forecasts (Harrison & Treagust, 2000). The development and utilization of scientific models are key practices in the fields of science and engineering (Bamberger & Davis, 2013). Models are utilized as tools to clarify and anticipate phenomena, represent the interactions among components in a system, and support problem solving and the exchange of ideas (Schwarz et al., 2009). Schneider (1984) and Vieira Kritz (2023) highlight three fundamental features that characterize models: (i) they are representations or mappings of their original objects; (ii) they always simplify the original object by representing only selected attributes; and (iii) the choice of these attributes is pragmatic and influenced by the model user, the timing of use, and the specific purpose of the model. The development and application of scientific models are critical practices in science and engineering, where they explain the interactions between system components. Developing and using scientific models is a crucial practice in science and engineering, where models serve to explain the interactions between components within a system (Donovan & Bransford, 2005). Although students may use models in ways that diverge from scientific usage, it is vital to immerse them in modeling practices that mirror the work of scientists, encompassing the processes of constructing, employing, assessing, and revising models.

However, scientific modelling is rarely integrated into the educational experiences of students at the elementary and secondary levels (Schwarz et al., 2009). There are often insufficient opportunities for students to engage with models, and many teachers do not have access to high-quality curricular materials that encourage the use of scientific modeling (Chiu & Lin, 2018; Chiu & Lin, 2019). Within this framework, the design-thinking approach has been shown to be an effective teaching method for enhancing students' creative self-efficacy and promoting their interest in modeling skills (He et al., 2023; Tsai et al., 2021). The design thinking process is an iterative approach that involves understanding users, identifying problems, designing optimal solutions, and conducting experiments. When applied in a STEM context grounded in ESD, this process can effectively enhance students' competencies by fostering critical thinking, creativity, collaboration, and real-world problem solving aligned with sustainability goals (Fan & Yu, 2017).

ESD empowers learners with the necessary knowledge, skills, and values to effectively navigate and respond to a fast-changing world, encouraging active participation in achieving Sustainable Development Goals (SDGs) (Setyowati et al., 2022). The core of ESD is fostering systemic thinking and analysis by engaging with real-world case studies, critical incidents, and project-based learning experiences. Current international discourse highlights eight core sustainability competencies essential for fostering transformative change (Brundiers et al. 2021, 2021). These include systems thinking competence, which involves understanding the relationships within complex systems and managing uncertainty; anticipatory competence, which focuses on evaluating future scenarios and potential consequences; and normative competence, which emphasizes reflecting on values and negotiating sustainability goals amid conflicting interests. Additionally, strategic competence is related to designing and implementing innovative sustainability actions, while collaborative competence involves empathizing and engaging in participatory problem solving. Critical thinking competence encourages questioning assumptions and reflecting on values, whereas self-awareness competence is about understanding one's role and responsibilities within the community. Finally, integrated problem-solving competence applies interdisciplinary approaches to develop inclusive and sustainable solutions (Rieckmann, 2022). Together, these competencies empower learners to become effective agents of transformative change.

Although many previous studies indicate that ESD and STEM-based methodologies can contribute to the development of 21st-century skills, most have not examined the specific function of STEM in modeling education within the context of ESD, utilizing design thinking (Hanif et al., 2019; He et al., 2023; Lin & Tsai, 2021; Lin et al., 2021). In fact, integrating STEM design thinking has the potential to add rich and relevant contextual dimensions to students, increasing their engagement in learning and training them in scientific modelling (Fan & Yu, 2017). Furthermore, the exploration of design thinking models has been conducted in the context of STEM education in secondary schools to increase student interest (Wingard et al., 2022).

Within a modeling-based viewpoint, the focus is on the construction and refinement of scientific models, as well as the interplay between teaching and learning processes, and the formation of mental models (Papaevripidou et al., 2014). The use of modeling can create a setting in which the construction and refinement of models yield higher-quality results than those currently attainable through other educational environments or resources (Louca et al., 2011). Through participation in these contexts, students can construct understanding models that support their internalization and lead to a more in-depth understanding of the phenomena being explored (Schwarz et

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al., 2009; Schwarz & White, 2005). Furthermore, the application of the STEM approach in educational settings is frequently general and does not prioritize direct relevance to real-life scenarios, which is vital for preparing students to address global issues and solutions in social, economic, and environmental contexts (Asrizal et al., 2022; Ladachart et al., 2022). Thus, more specific research is required to analyze the effects of educational models that merge the STEM design thinking approach with ESD issues in enhancing students' abilities in scientific modeling.

Literature Review

Integrating STEM design thinking into ESD has shown considerable promise in strengthening students' scientific modeling skills at all educational levels. Yalçın (2024) stated that design-based STEM activities can substantially and durably improve 21st century competencies, such as life and career skills, innovation and learning abilities, and digital literacy, even in preschool-aged children. This suggests the significant early developmental potential of such interventions in enhancing scientific modeling skills. This aligns with the findings of Papadakis and colleagues, who demonstrated that developmentally appropriate mobile applications, programming platforms like App Inventor, and robotic kits such as Lego Mindstorms NXT can effectively foster computational thinking and STEM-related skills in early childhood and teacher education contexts (Kalogiannakis & Papadakis, 2020; Papadakis, 2019; Papadakis & Orfanakis, 2017).

Furthermore, the use of design-based pedagogy and tools, such as 3D printing, in integrated STEM programs has been linked to a better understanding of the design process and mindset needed for effective scientific modeling (Zhou et al., 2020). Systems thinking and conceptual modeling have also been promoted through interdisciplinary approaches, which significantly benefit both engineering students and educators (Peretz et al., 2023). Experiential learning methods, such as field trips and collaborative learning, have proven effective in developing students' systems thinking abilities by immersing them in complex real world contexts (Demssie et al., 2023).

Studies increasingly emphasize that incorporating models into science curricula is indispensable for nurturing students' scientific literacy and problem-solving competencies. Innovations in technology now allow easier model manipulation and refinement, supporting a more hands-on and evolving approach to science education and research. The application of models in educational contexts, as demonstrated by numerous studies, emphasizes their importance in promoting a more profound comprehension of intricate phenomena. For instance, Peretz et al. (2023) underscored the importance of applying mathematical modeling to real-world scenarios, demonstrating how such models can connect theoretical mathematical concepts with their real-life applications. Böschl et al. (2023) highlighted the importance of incorporating authentic scientific modeling practices in elementary classrooms, noting that while students often engage in model construction, there is a lack of opportunities for model evaluation and revision, which are crucial for a comprehensive understanding of scientific phenomena. The use of machine learning to assess student-developed models, as explored by Zhai et al. (2022), demonstrates the potential of technology to provide timely feedback, thus supporting teachers in integrating modeling tasks into their instruction. Bowers et al. (2023) further explored the role of computational system modeling in education, emphasizing the importance of testing and debugging as part of the modeling process, which helps students refine their models and deepen their understanding.

Therefore, fostering scientific modeling skills through the integration of STEM-MDT within the context of ESD is crucial to align science education with the epistemic knowledge framework outlined in the Programme for International Student Assessment (PISA) (OECD, 2025). Scientific modeling enables students to construct and evaluate representations of complex phenomena, predict outcomes, and propose core competencies for solutions, as emphasized in the PISA framework (OECD, 2025; L. Zhang et al., 2023). Through modeling, students developed a deeper understanding of the nature and purpose of science, the distinction between models and reality, and the limitations and predictive power of different types of models. This approach not only equips learners to engage with sustainability challenges in meaningful ways but also prepares them to meet international benchmarks of scientific literacy and inquiry based competence as defined by PISA.

Research Aim and Research Question

STEM Modelling Design Thinking (STEM MDT) is a learning model that integrates STEM education with the design thinking approach at the level of real world applications, aiming to improve scientific modelling skills. This study aimed to compare the effects of STEM MDT and project-based learning (STEM PjBL) models in enhancing students' scientific modelling skills within the context of ESD issues. Through a more detailed analysis of the effect

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sizes on each aspect of scientific modelling skills, this research is expected to strengthen empirical evidence on the effects of STEM MDT. The findings of this study are expected to provide significant contributions to pedagogical frameworks and encourage educators and policymakers to consider STEM MDT a breakthrough innovation in science education. The guiding research question for this study was:

What were the effects of the STEM-MDT learning model on scientific modelling skills compared with the STEM-PjBL learning model in the context of ESD issues?

Research Methodology

General Background

This study employs a quasi-experimental methodology that incorporates a pretest-posttest design along with a nonequivalent control group (Reichardt, 2019). The process includes collecting data before and after the intervention in two groups: one group receiving treatment and the other functioning as a control, as shown in Figure 1 (Creswell, 2018). The steps in the research procedure are as follows: first, a pretest measuring scientific modeling capability is given to both the experimental group and the control group; second, implementing the STEM Modelling Design Thinking (STEM MDT) in the experimental group (EG) and the STEM Project-Based Learning (STEM PjBL) in the control group (CG); third, administering a posttest on scientific modeling ability for both groups. The effects of the STEM MDT were evaluated by analyzing and comparing the pretest and posttest scores for each aspect of scientific modelling ability between the two groups. Conducted over four weeks, this study was implemented in science classes at SMP IT Nur Hidayah Surakarta from October to December 2024. The educational content focused on climate change issues in the context of ESD (Shaw et al., 2021).

This study was conducted in accordance with ethical standards involving research with human participants. Prior to the implementation of the research, written informed consent was obtained from all participating students and their guardians. Participation in the study was voluntary, and anonymity and confidentiality of participants' responses were maintained throughout the research process. Ethical approval for the study was granted by the Surakarta City Education Office (Approval Letter Number: PN.01/7532/VIII/2024), which facilitated coordination between the participating schools. The testing procedures were approved by both school principals and science teachers, who directly supervised the implementation. Furthermore, a permission letter (Number: 17651/UN27/PK/PK.03.08/2024) was issued to SMP IT Nur Hidayah, allowing data collection from respondents without coercion. Before data collection, all students were thoroughly informed of the purpose and procedures of the study. The study ensured that participation was fully voluntary, complete confidentiality and anonymity were guaranteed, and informed consent was obtained from all students who participated in the scientific modeling evaluation. This approval confirmed that the study complied with national research ethics policies and adhered to international ethical guidelines, including the principles outlined in the Declaration of Helsinki. Although the study was quasi-experimental and not a clinical trial, the reporting structure was reviewed against relevant items from the CONSORT 2010 checklist to ensure transparency, methodological integrity, and ethical compliance.

To ensure fidelity of implementation, the science teacher in the experimental group participated in a two-day intensive training focused on core components of the STEM Design Thinking framework, such as problem identification, scientific modelling, ideation, prototyping, and iterative refinement (Kelley et al., 2020). The training was guided by structured modules, standardized lesson plans, and sample teaching scripts to ensure consistency across instructional sessions (Chevalier et al., 2020). During this training, the teacher also facilitated group discussions, guided student investigations, and evaluated modelling outcomes based on the developed rubrics.

To minimize potential teacher bias, the teachers assigned to the experimental and control groups were different individuals with similar implementation phases by independent observers using structured fidelity checklists and evaluation rubrics(Huang et al., 2022). Additionally, teacher reflection journals and debriefing interviews were used to support continuous improvement and ensure alignment with the intended instructional model. Both the experimental and control groups were taught by teachers with qualifications and teaching experience comparable to the control for teacher effects (Ragusa, 2011), and weekly coordination meetings helped ensure consistent implementation across classrooms (Latip et al., 2023).Weekly coordination meetings involving the research team and classroom teachers were held to address implementation challenges, reinforce pedagogical fidelity, and clarify instructional procedures (Latip et al., 2023). Furthermore, participant selection was carefully performed to ensure comparability between the experimental and control groups. Students were matched based on grade level, prior academic performance in science, and gender distribution. This matching strategy is essential for controlling

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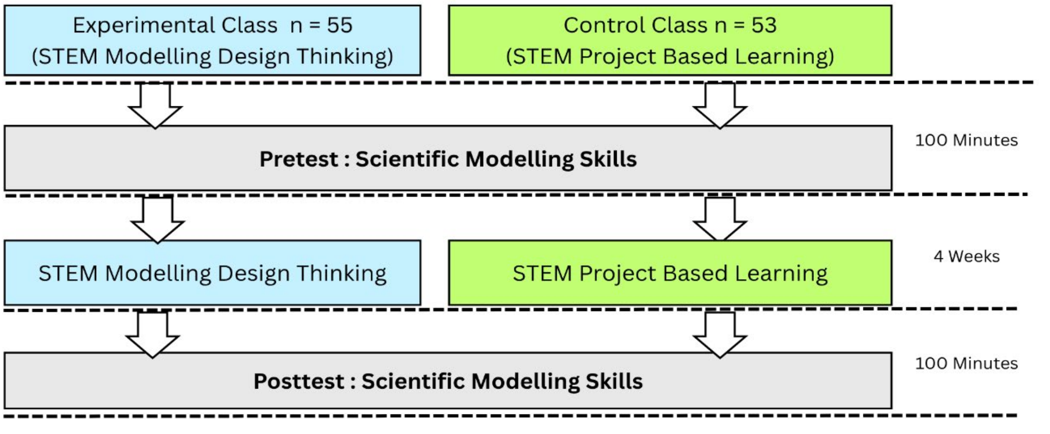
extraneous variables and enhancing internal validity (Balkin & Lenz, 2021; Reichardt, 2019). Collectively, these methodological strategies include comprehensive instructor training, mitigation of teacher bias, fidelity monitoring, consistent instructional tools, and matched group selection aligned with best practices in quasi-experimental research design, and contributed to the robustness of the study's internal validity (Skourdoumbis & Gale, 2013).

Figure 1
Procedure of Experiment



Initially, both classes underwent a pretest to assess their scientific modeling skills, which lasted 100 minutes and was conducted in October 2024. The study, involving both experimental and control classes, was conducted over four weeks from October to December 2024. During this period, the experimental class participated in STEM Modelling Design Thinking (STEM MDT), while the control class engaged in STEM Project Based Learning (STEM PjBL). After the four-week period, both classes took a posttest to evaluate their scientific modeling skills again, which lasted for 100 minutes. This structured approach enabled a comparative analysis of the effects of different STEM educational methodologies implemented from October to December 2024.

Population and Sample

The study population consisted of 181 ninth-grade students at SMP IT Nur Hidayah Surakarta, a private institution located in Central Java, Indonesia. Using purposive sampling, the sample was selected based on relevant criteria that focused on ninth-grade students in science, where the curriculum includes topics related to climate change in accordance with national standards. The criteria align with the purpose of this study, which is to evaluate how the STEM MDT affects the improvement of scientific modeling skills related to climate change. The purposive sampling method was used because researchers could selectively choose samples according to the characteristics of the phenomenon under study, thus obtaining significant information about this study. The chosen sample comprised 55 ninth-grade students in the experimental group and 53 in the control group. The sample size was determined based on the number of participants who met the inclusion criteria. These criteria included willingness to participate, ability to participate in the intervention, and ensuring a balanced group size to facilitate a comparative analysis. The Experimental Group (EG) used the STEM MDT, whereas the Control Group (CG), serving as a comparison of the experimental outcomes, employed STEM PjBL. The selected research participants were both capable and willing to participate in this study while ensuring the confidentiality of their identities. This approach minimizes potential selection bias and improves the internal validity of the study (Changwong et al., 2018).

Procedures

Experimental groups

The experimental group was treated by applying the STEM MDT, which has the advantage of incorporating minds-on and hands-on designs in scientific modeling practices through the phases of science and engineering,

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focusing on climate change issues as the main problem presented in learning. This acts as a stimulus for students to engage in scientific modeling, thereby improving their understanding. Climate change issues in this experimental group were integrated with ESD aspects, which involved environmental, social, and economic dimensions. This integration facilitates the exploration of diverse perspectives through discussion. The process of selecting the experimental class for research is an important step that deserves careful attention. This selection process considered the characteristics of the participants in accordance with the research objectives.

In this experimental group, the STEM MDT learning model represented an integration of the STEM approach and modeling components. The elements of the STEM MDT model consisted of (1) a learning syntax with five phases, (2) social systems, (3) reaction principles, (4) support systems, and (5) instructional impacts. The phases and subphases of the STEM MDT learning model are systematically arranged frameworks that direct students in solving scientific and social problems from the problem orientation stage to the reflection stage. These phases illustrate the essential steps in the learning process designed to achieve the intended outcomes, while the sub-phases provide more granular steps within each phase that support students' participation in a structured learning experience. The phases and subphases of the STEM MDT learning model are listed in Table 1.

Table 1
Phases and Subphases of STEM MDT

Phases	Sub-Phase	Learning Activity
		Phase 1: Scientist
Empathize	Observation	Observing phenomena or situations to gather initial information and explore user needs through direct observation and interaction, based on the ESD context: economy, society, environment.
		Conducting experiments or interventions to understand phenomena based on the ESD context obtained from the empathize phase.
Define	Manipulation	
Modelling	Minds On modelling (initial Model)	Creating representations of proposed solutions, such as diagrams, simulations, models, patterns, or relationships, using tools like SageModeler, Canva, or mind mapping in ESD contexts.
	Verification (model revision)	Re-testing hypotheses or models with additional data or further information based on ESD.
	Application (final Model)	Applying model results in real-world contexts or new problems based on the ESD contexts.
		Phase 2: Engineer
Ideate	Pursue Solutions (hands-on modelling)	Formulating solutions to defined problems based on user needs and developing various ideas and potential solutions through technological design based on the ESD contexts.
Prototype	Explore the Question	Deeply exploring user questions based on modeling results and creating prototypes or initial versions of selected solutions, both physical and digital, based on the ESD contexts.
	Engage in Collaborative Activities	Collaborating with others on projects to develop product solutions in design modeling based on strong theoretical foundations related to the ESD contexts.
	Use Learning Technologies and Other Scaffolds	Using technology and other learning aids for product solutions based on the ESD contexts.
Test	Create Artifacts	Testing prototypes with users or in real contexts, then collecting feedback and conducting evaluations based on the ESD contexts.

The outlined learning framework consists of two main phases: scientists and engineers, each with specific sub-phases focused on ESD. In the "Scientist" phase, students begin by empathizing through observation to gather information about phenomena and user needs within ESD contexts. Then, they conducted experiments to deepen their understanding. In the "Define" subphase, students create initial models using tools like SageModeler and Canva, followed by verifying and applying these models to real-world problems related to ESD. The "Engineer" phase starts with ideation, where students formulate solutions to defined problems based on user needs and develop ideas through technological design. They explore user questions, create prototypes, and engage in collaborative activities to develop product solutions grounded in ESD principles. Finally, in the "Test" subphase, students test their prototypes in real contexts, gather feedback, and refine their solutions. This framework promotes critical thinking and creativity, while preparing students for complex challenges in sustainable development.

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Control Groups

The control group was treated with STEM Project-Based Learning (PjBL), a method that is usually conducted by science teachers. The STEM PjBL model is a learning approach that does not incorporate modeling activities in the classroom. Instead, it focuses on general issues related to climate change that culminate in product output. The primary difference in the intervention between the two groups lies in the implementation of the learning model. The integration of scientific modeling within the context of ESD at the real-world application level is a distinctive feature of the experimental group, whereas the control group only applies STEM project-based learning without any additional innovations. Table 2 provides a comprehensive overview of the learning steps in the inquiry model used in the control group.

Table 2
Learning Steps and Learning Activity of STEM Project Based Learning

Steps	Learning Activity
Reflection	Guide students into the context of problems, enabling them to understand and generate ideas for solutions.
Research	Facilitate discussions that may challenge and deepen the students' understanding of problem solving.
Discovery	Organize students into groups to analyze information and present their solutions to problems.
Application	Evaluate the products created by students, allowing them to integrate STEM concepts at this stage.
Communication	Share the results of the project to enhance communication skills related to problem solving.

Source: (Laboy-Rush, 2015; Putri & Dwikoranto, 2022)

The learning process consists of five key steps: reflection, research, discovery, application, and communication, each designed to enhance students' problem-solving abilities within a collaborative framework (Laboy-Rush 2015; Putri & Dwikoranto 2022). In the Reflection step, students are guided into the context of specific problems, which helps them to understand the issues at hand and generate ideas for potential solutions. This foundational understanding is further developed during the research phase, where discussions are facilitated to challenge students' perspectives and deepen their comprehension of the problem solving process. Following this, the Discovery step involves organizing students into groups, allowing them to analyze information collaboratively and present their proposed solutions to the identified problems. In the application phase, students evaluate the products they have created, integrate STEM concepts into their work, and reinforce their understanding of the subject matter. Finally, the Communication step encourages students to share the outcomes of their projects, enhancing their communication skills and fostering a collaborative environment focused on effective problem-solving. This organized approach not only fosters critical thinking and collaboration but also equips students to effectively address real-world challenges. Project-based learning (PjBL) is widely accepted by educators and communities as an effective method of motivating students, particularly when teachers receive strong administrative support. In problem-based environments, students excel, driven by construction, social context, and community connections (Miller & Krajcik, 2019).

Data Collection Instrument

The assessment, intended to measure students' skills in scientific modeling, comprised 10 carefully designed questions. These questions assess students' abilities in scientific modeling, focusing on key aspects, such as: (1) Can the model explain all observations? (2) How can the model be used to predict the behavior of a system when manipulated in specific ways? (3) How does the model align with other concepts related to the functioning of the world and other scientific models? This approach not only establishes a connection between theoretical concepts and practical applications but also bridges the gap between abstract knowledge and real-world experiences. Furthermore, scientific modeling encourages students to actively construct their understanding of nature through observation, experimentation, and analysis (Wan et al., 2021). By refining their modeling skills, students can enhance their scientific literacy while acquiring transferable skills applicable to various disciplines, including logical reasoning, data interpretation, and effective communication. The assessment of students' scientific modeling skills incorporates aspects adapted from (OECD, 2022) and (Harline et al., 2021), tailored to the topic of climate change. Table 3 presents the aspects and indicators used in this study.

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Table 3
Aspects and Indicators of Scientific Modelling Skills

Aspect	Description	Indicator
Question	Identify the main question to be answered or the problem to be solved in the scientific process.	Given a weather model, students can formulate several questions based on the information from the fundamental concepts of weather
	By analyzing various climate models, such as weather, seasonal, and climate models, students formulate relevant questions that deepen their understanding of climate systems.	Given a seasonal model, students can formulate several questions based on information from the fundamental concepts of seasons
Plan	Plan the methods, steps, and resources needed to answer the question or solve the problem.	Given a climate model, students can formulate several questions based on the information from the fundamental concepts of climate.
	Identify critical challenges linked to climate change, such as the consequences of fossil fuel consumption, changes in land use, and the impact of policy choices.	Given a model of annual climate change factors, students can analyze issues related to the scientific model of the factors causing climate change
Build	Develop or construct the model, experiments, or instruments needed to answer the question or solve the problem.	Using a model of global greenhouse gas emissions, students can explain how human activities, particularly the combustion of fossil fuels, lead to higher concentrations of greenhouse gases in the atmosphere
	Builds the capacity to understand and communicate the interconnected nature of human actions, carbon cycles, and climate outcomes	Given a carbon cycle diagram, students can model how changes in this cycle can affect the global climate balance
Test	Conduct trials or experiments to obtain data and analyze the results according to the established plan.	Given a model of the impacts of climate change, students can explain the effects of rising sea levels
	fosters an understanding of the interconnectedness of climate change, agriculture, and food security, equipping students to address real-world challenges	Using a model that illustrates the impacts of climate change, students can describe how rising sea levels affect agriculture.
Revise	Review and improve the model, experiments, or processes based on the results to enhance accuracy or effectiveness.	Given a model of the effects of climate change on public health, students can explain the impact of the increase in weather-related disease occurrences
Share	Communicate the results, findings, or models to relevant audiences and receive feedback for further improvement.	Given a model of the effects of climate change, students can explain the impact on food security

The instrument designed to assess scientific modeling skills was subsequently validated, which included both content and construct validation processes (Ulya & Rosnawati, 2024). The content validity evaluation showed that all items in the question achieved an Aiken score (V) higher than .76, which confirms that all items are valid. To evaluate the validity of the construct, the questions were administered to ninth-grade students who had completed 2 years of lower secondary education. The construct validity test using the Rasch model analysis yielded a Cronbach's alpha value of .61, suggesting that the instrument is reliable. Although this Cronbach's alpha value indicates reasonably good reliability, further analysis revealed that the instrument has an explained variance value of 39.1%. The Eigenvalue was satisfactory, as it did not exceed the threshold of 3 (Mokshein et al., 2019). Meanwhile, the unexplained variance ranges from 7.80% to 13.10%. This indicates that the instrument is effective in measuring scientific modeling skills (Fisher, 2018). The essential unidimensionality (Rasch/common variance) was 62.8%, confirming that the instrument effectively measured a single construct. Before learning began, the students worked on the pre-test questions for scientific modeling skills for 100 minutes. After the learning was completed, the students answered the post-test questions for scientific modeling skills for 100 minutes. Further analysis of the data showed that the average total score for the 108 participants was within a maximum score of 100 and a minimum score of 56.8. The reliability of the instrument based on model analysis indicated a real RMSE value of 1.01 and a person reliability of .43. For the items, reliability demonstrated a very good value with an item reliability of .98. Although the person reliability value was relatively low, the overall psychometric analysis confirmed that the instrument remained valid and reliable for assessing students' scientific modeling skills, particularly at the group level. A high item reliability score reflects a well-constructed and consistently functioning set of items that align with the intended constructs.

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The instrument also showed acceptable item fit indices and logical progression of item difficulty, which supports its construct validity. The relatively lower person reliability may be attributed to the homogeneity of the sample or the range of abilities of the participants. However, this does not undermine the instrument's ability to detect significant differences between the experimental and control groups, as demonstrated by quasi-experimental findings. Therefore, the instrument is considered appropriate for research purposes in educational settings, especially when examining group-level learning outcomes in interventions related to STEM and sustainability education. In general, this instrument has proven valid and reliable for measuring scientific modeling skills.

Data Analysis

The analysis of the data from the scientific modelling skills test involved comparing the mean scores of the pretest and posttest. First, the normality distribution of the test data was assessed using the Shapiro-Wilk test. The Shapiro-Wilk test results for the pretest and posttest scores in both the control group (CG) and experimental group (EG) indicated $p > .05$, confirming that the data followed a normal distribution. Furthermore, the Levene test was conducted to evaluate the homogeneity of variance for the pretest and posttest scores in CG and EG, yielding $p > .05$, which indicated that the data were homogeneous. Parametric statistical tests were used to analyze the differences in scientific modeling skill scores between the CG and EG.

Additionally, a paired sample *t*-test was performed to assess the differences in average scores between the pretests and posttests for each aspect of scientific modeling skills in both the control group (CG) and the experimental group (EG). An independent sample *t*-test was also conducted to evaluate the differences in the average post-test scores between the CG and EG for each aspect of scientific modeling skills. The effect size for each aspect of scientific modelling skills in CG and EG was analysed using Cohen's Effect Size (Cohen, 1988).

Research Results

The STEM MDT was applied to the experimental group (EG), while STEM PjBL was used in the control group (CG) during science instruction. Before the start of the learning process, students completed pretest questions, and at the conclusion of the instruction, answered posttest questions. The pretest scores reflect the students' scientific modeling skills before the intervention, whereas the posttest scores offer insight into their scientific modeling skills after the implementation of the STEM MDT. Table 4 presents the descriptive statistics for the pretest and posttest scores of scientific modeling skills.

Table 4
Descriptive Statistics of the Pretest and Posttest

Aspect	Group	*n*	*M*		*SD*		Minimum		Maximum	
			Pre	Post	Pre	Post	Pre	Post	Pre	Post
Question the problem	CG	53	65.80	7.31	11.8	8.83	25	43.75	62.5	95
	EG	55	72.19	88.18	7.28	12.6	50	75	75	100
Plan the Solution	CG	53	56.84	62.76	14.2	14.77	25	43.75	43.75	100
	EG	55	69.04	79.02	11.74	13.09	25	75	77.5	100
Build the Solution	CG	53	65.09	73.11	11.06	14.17	37.5	50	75	100
	EG	55	72.54	88.18	7.10	12.60	50	75	81.25	100
Test Product	CG	53	62.03	67.86	13.19	17.43	37.5	50	75	100
	EG	55	72.02	81.69	8.56	12.09	50	75	77.5	100
Revise Product	CG	53	63.92	71.11	1.87	13.27	50	62.5	75	100
	EG	55	73.33	88.90	4.27	12.82	50	75	75.25	100
Share Product	CG	53	62.03	69.10	1.95	12.88	50	43.75	75	100
	EG	55	72.12	81.30	8.130	12.47	50	75	81.25	100

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Aspect	Group	*n*	*M*		*SD*		Minimum		Maximum	
			Pre	Post	Pre	Post	Pre	Post	Pre	Post
Overall Mean	CG	53	62.62	69.04	12.01	13.56	37.50	48.96	67.71	99.17
	EG	55	71.87	84.54	7.85	12.61	45.83	75.00	77.96	10.00

Table 4 indicates that overall, the mean post-test scores were higher than the pre-test scores in both the control group (CG) and the experimental group (EG). This pattern was also evident in each aspect of scientific modeling skills, where the average post-test scores surpassed the pre-test scores in both groups. However, when comparing the overall average pretest and posttest scores between CG and EG, the average score in EG was markedly higher than in CG. This disparity can be attributed to the different interventions that were implemented in each group. In CG, the intervention focused on STEM learning without integrating the aspects of modeling and ESD. In contrast, the EG intervention used the STEM MDT model, which emphasizes scientific modeling skills and ESD, incorporating the social, environmental, and economic dimensions. These differing pedagogical approaches resulted in variations in the enhancement of scientific modeling skills, culminating in higher average scores in the EG than in the CG. Additionally, a paired sample *t*-test was used to analyze the mean scores from the pretest and posttest, determining the differences in average scores for each facet of scientific modeling skills in the control group (CG) and experimental group (EG) (see Table 5).

Table 5
Comparison of Improvement in Scientific Modelling

Aspect	Group	*N*	Paired Sample *t*-test		Effect Size (ES) *(Cohen's d)*	
			t-value	*p*-value	Point Estimate	Interpretation
Question the problem	CG	53	-2.47	.02	.34	Small
	EG	55	-7.58	<.01	1.02	Large
Plan the Solution	CG	53	-2.13	.04	.29	Small
	EG	55	-6.24	<.01	.84	Large
Build the Solution	CG	53	-4.57	.00	.63	Moderate
	EG	55	-11.17	<.01	.94	Large
Test Product	CG	53	-2.31	.03	.32	Small
	EG	55	-6.16	<.01	.75	Moderate
Revise Product	CG	53	-3.61	.00	.50	Small
	EG	55	-11.95	<.01	1.16	Large
Share Product	CG	53	-3.71	.00	.51	Moderate
	EG	55	-5.75	<.01	.72	Moderate
Overall Mean	CG	53	-3.13	.00	.43	Small
	EG	55	-8.14	.01	.91	Large

The findings presented in Table 5 of the paired sample t-test reveal that the pretest-posttest scores for each aspect of scientific modeling skills in both the control group (CG) and the experimental group (EG) showed significant differences ($p < .05$), except for the aspect of planning and implementing the solution in CG, which was not significant ($p > .05$). In terms of effect size (ES), it is noted that in EG, three aspects fall into the very large category and one aspect falls into the large category, while in CG, three aspects fall into the moderate category, and one aspect falls into the small category. Overall, the effect size (ES) in the experimental group (EG) was greater than that in the control group (CG), indicating that the STEM MDT learning model intervention in EG had a more significant positive impact on scientific modeling skills than the STEM PjBL learning intervention in CG. Furthermore, an independent sample *t*-test was performed to analyze the average post-test scores and determine the significance of the differences between the EG and CG (Table 6).

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Table 6
Independent t-test of Scientific Modelling

Aspect	Group	*n*	Independent Sample *t*-test (Sig.)		Effect Size (ES) *(Cohen's d)*	
			t-value	*p*-value	Point Estimate	Interpretation
Question the problem	CG	53	-6.18	< .001	.84	Large
	EG	55				
Plan the Solution	CG	53	-3.85	< .001	.52	Moderate
	EG	55				
Build the Solution	CG	53	-3.25	< .001	.92	Large
	EG	55				
Test Product	CG	53	-3.97	< .001	.54	Moderate
	EG	55				
Revise Product	CG	53	-6.48	< .001	.88	Large
	EG	55				
Share Product	CG	53	-4.78	< .001	.65	Moderate
	EG	55				
Overall Mean	CG	53	-4.75	< .001	.73	Large
	EG	55				

Table 6 indicates that there were significant differences ($p < .05$) in post-test scores between the experimental group (EG) and the control group (CG) in all dimensions of scientific modeling skills. These results imply that the STEM MDT intervention in the EG is more effective than the intervention in the CG for improving scientific modeling skills. The effect size (ES) analysis shows that three aspects are classified as large, whereas three aspects are categorized as moderate. The STEM MDT provides students with the skills necessary for engaging in scientific modeling and planning alternative solutions, thus facilitating their training in the implementation of these solutions. In summary, these findings highlight that STEM MDT significantly enhances students' scientific modeling skills in comparison to the interventions utilized in CG.

Discussion

The findings of this study revealed a significant improvement in scientific modeling skills, particularly in the experimental group (EG) that received the STEM Modelling Design Thinking (STEM MDT) intervention. Both the control group (CG) and the EG showed gains from pre-test to post-test, yet the improvement was markedly higher, confirming the intervention's effects. Analysis in six dimensions of modeling skills demonstrated statistically significant improvements in the EG, with three aspects achieving a 'very large' effect size (ES > .8), one categorized as "large," and an overall effect size of .91 that contrasts sharply with the CG's moderate ES of CG of .43 (Cohen, 1988). These results underscore the positive and robust impact of the STEM MDT model in developing students' scientific modeling competencies (Krell & Krüger, 2016).

A closer look at posttest performance confirms that gains occurred across all components of modeling assessed in this study (Aiman & Hasyda, 2020; Alrawili et al., 2020; Miller et al., 2020). The success of the STEM MDT model can be attributed to its structured integration of design thinking principles with authentic scientific modeling practices, creating a more engaging, iterative, and applied learning environment (Donovan & Bransford, 2005). These outcomes align with previous literature advocating STEM-based, project-oriented, and inquiry-driven pedagogies to improve modeling proficiency. Furthermore, the artifacts illustrate a clear improvement path, evolving from rudimentary models with two to three variables into more sophisticated representations that integrate additional key variables (e.g., carbon emissions and rainfall patterns), intricate causal relationships, and evidence-based refinements. These iterations contributed to deeper scientific explanations and more dynamic system-based reasoning, although some students still required scaffolding to fully articulate their understandings (Bielik et al., 2018; Chiu & Lin, 2019).

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The iterative nature of the modeling process was pivotal in helping students refine their conceptual understanding, confront misconceptions, and internalize complex scientific ideas. This process supports the assertion that effective inquiry instruction should model scientific thinking (Crawford, 2000). The STEM MDT framework offers a concrete structure for classroom implementation, emphasizing the lived experience of modeling development over abstract theoretical critiques (Chiu & Lin, 2019). The involvement of the students in the design thinking phases (empathizing, defining, ideating, prototyping, and testing) was particularly visible in their sustainable housing projects (Dam & Siang, 2025; Mundy et al., 2024). These tasks prompted students to address climate-related issues, incorporating principles of ESD such as material sustainability, environmental impact, and social responsibility (Sutinah et al., 2024). Educators observed that students showed increased engagement and curiosity while actively investigating real-world issues, which enhanced their comprehension of sustainability challenges within STEM-based learning, which incorporates scientific modeling related to ESD topics (Van Driel & Verloop, 2002b).

The significant difference in effect sizes between the EG and CG further validates the capacity of the design thinking model to enrich scientific modeling skills. The integration of ESD within the STEM MDT framework allowed students not only to engage in modeling tasks but also to reflect critically on complex socio-environmental systems. As a result, students developed stronger competencies in scientific reasoning, problem solving, and innovation, which are essential for navigating 21st century challenges. Supporting this evidence, research by Yalçın & Erden (2021) in STEM education indicates that the application of data obtained from research diaries significantly enhances children's communication and interaction skills, fosters peer learning, promotes cooperation, boosts self-confidence, instills a sense of responsibility, encourages problem-solving and idea generation, and improves empathy skills.

Integrating ESD in Science Education through STEM MDT

Integrating ESD into science learning through scientific modeling is crucial for transforming abstract concepts into tangible understandings. At the practical application level, this integration serves as an essential intervention to motivate students to comprehend and analyze complex sustainability issues while simultaneously developing viable solutions through structured modeling processes (Griffith & Lechuga-Jimenez, 2024; Hebebci & Usta, 2022). Within the context of ESD, these phases holistically address the environmental, social, and economic dimensions (UNESCO, 2024). Specifically, the initial empathization phase involves students observing real-world phenomena, gathering initial insights, and identifying stakeholder needs through direct observation and interaction. At this stage, students are encouraged to investigate sustainability issues from multiple perspectives, encompassing economic, social, and environmental aspects. Internationally, there is increasing emphasis on fostering competency development through ESD. Scholars, such as Rieckmann 2022), have identified eight core sustainability competencies essential for advancing sustainable development, particularly within sustainability science programs. Among these competencies, systems thinking is emphasized as essential. It encompasses the ability to identify and understand relationships, analyze complex systems, grasp how systems are interconnected across different fields and scales, and navigate uncertainty. Within systems thinking, scientific modeling is employed to interconnect concepts and subconcepts into a coherent whole (Brundiers et al., 2021; Rieckmann, 2022). In the STEM MDT learning approach, the empathizing phase specifically involves observing natural phenomena and translating these observations into environmental, social, and economic aspects.

The empathize phase specifically involves students who observe natural phenomena and translate these observations into the environmental, social, and economic dimensions. Subsequently, in the define phase, students formulated a structured plan based on their observational findings, clearly identifying core problems that are contextually relevant and sustainable. This planning stage serves as a foundation for strengthening the initial modeling framework, allowing students to connect preliminary data with underlying scientific concepts related to observed issues. The modelling phase represents the core of scientific modeling skill development, in which students construct conceptual models through scientific reasoning and link various elements within complex systems (McNeill et al., 2004; Zuhri & Wilujeng, 2023). Initial models may take the form of diagrams, schemes, or simple physical representations illustrating relationships among variables such as temperature, humidity, and rainfall within a local climate system (Bamberger & Davis, 2013; Van Mil et al., 2013). After constructing the initial model, students proceeded to develop alternative solutions and assess the feasibility of the model through preliminary simulations or discussions, requiring divergent thinking and the synthesis of multiple scientific solutions (Alonzo et al., 2022; Berland & McNeill, 2010; Schwarz et al., 2009). In the prototype phase, the conceptualized model is transformed into a tangible prototype or a concrete model that can be tested. This stage allows students to revise their initial models based on experimental results or functional tests, thereby deepening their understanding of

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the interconnections between scientific concepts and processes (Schwarz et al., 2009). Finally, in the test product phase, the completed product was evaluated to determine the effectiveness of the model in explaining or solving the identified problem. This phase also includes a sharing process in which students present their model development outcomes to an audience or community and receive feedback (Buntha et al., 2024).

Empirical evidence from the EC and CG classrooms, as presented in Table 5, supports each phase of the STEM MDT approach, demonstrating significant impacts on various aspects of scientific modeling skills. The processes involved in scientific modeling skills not only lead to the creation but also serve as a progressive learning sequence, encompassing the formulation of questions, design of conceptual models, development of prototypes, and communication of results through scientifically supported modelling activity. This comprehensive process reflects the integration of scientific modeling within an educational context oriented toward sustainability (ESD). The STEM MDT offers significant advantages that substantially enhance students' educational experiences. First, it combines various disciplines of science, technology, engineering, and mathematics within a design thinking framework, allowing students to grasp the interconnectedness of these fields (Bosman & Eom, 2019; Dam & Siang, 2025; Fan & Yu, 2017). This approach emphasizes problem solving by encouraging students to identify and address real-world issues relevant to social, economic, and environmental contexts, thus developing critical and creative thinking skills.

Additionally, STEM MDT focuses on cultivating modeling skills and empowering students to create conceptual representations of complex systems, an essential competency in scientific and engineering practices. The project-based learning component immerses students in hands-on experiences, deepening their understanding and knowledge retention (Baran et al., 2021; Maida, 2011; Miller & Krajcik, 2019). Furthermore, it promotes active student engagement, boosting motivation and interest in STEM subjects, while fostering collaboration and communication skills through teamwork. By integrating the principles of ESD, students learn to consider the environmental, social, and economic impacts of their solutions and prepare them to become responsible future leaders (Riess et al., 2022). The iterative and reflective nature of the process encourages learning from mistakes and refining solutions, thus cultivating a lifelong learning mindset. Supported by empirical evidence demonstrating significant improvements in modeling skills and systems thinking, the STEM MDT approach effectively equips students to address today's complex, interconnected global challenges.

Through the integration of real-world problems, interdisciplinary content, and reflective practices, students can not only construct meaningful scientific models but also apply these models to analyze environmental, social, and economic issues aligned with the Sustainable Development Goals (SDGs). This capacity to transfer knowledge across contexts signifies a deeper understanding of science as a tool for informed decision making and societal contributions. Integrating STEM Design Thinking with ESD is essential for equipping students with competencies to address global issues such as climate change and environmental degradation. This approach aligns with PISA frameworks that emphasize the application of scientific knowledge and evidence-based reasoning in real-world contexts (OECD, 2025). It fosters systems thinking and cross-cutting competencies, such as ethical decision making and data literacy, through pedagogical strategies such as self-regulated learning (Demssie et al., 2023), service learning (Martn-Sánchez et al., 2022), and socioscientific issue integration(Van Der Veen, 2023). In the modeling process, students are guided to identify and analyze the interrelationships among variables, an essential aspect of systems thinking, enabling them to construct conceptual models that reflect the dynamic and interconnected nature of real-world phenomena. The use of outcome indicators to assess ESD implementation ensures progress toward sustainability competencies (Cebrián et al., 2021), while teacher capacity-building programs incorporating future studies help educators prepare students for uncertain and complex global realities (Khadri, 2022). Initiatives such as Smithsonian Science for Global Goals demonstrate how data-driven STEM education and science communication can engage students in solving real-world problems within their communities (Gibson et al., 2023). Ultimately, hands-on STEM projects and citizen science initiatives provide transformative experiences that not only enhance modeling skills but also prepare students to become responsible and informed global citizens (Batchelder et al., 2023; Greif et al., 2020; Miller & Krajcik, 2019; Rott et al., 2024). As students increasingly recognize the importance of sustainable development, educational institutions must adapt their curricula to integrate economic, social, and environmental issues, thus preparing students for future challenges (Zwolińska et al., 2022).

STEM MDT's Contribution to Sustainable Development Goals (SDGs)

This study makes a significant theoretical contribution to future-oriented science education by illustrating how the integration of ESD within the STEM MDT framework enhances both students' scientific modeling skills and their transformative competencies. The incorporation of design thinking phases in STEM MDT facilitates inquiry-

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based and modeling-based learning that aligns with the core science and engineering practices articulated in the Next Generation Science Standards (NGSS), including developing and using models, constructing explanations, and designing solutions. This approach reflects and extends the work of Schwarz et al. (2009), who conceptualize scientific modelling as an essential epistemic practice by applying it to authentic and socially relevant sustainability contexts. Furthermore, the model encourages the development of transformative competencies, such as systems thinking, anticipatory thinking, and agency to sustainable action, as emphasized in the OECD Learning Compass 2030 and UNESCO's ESD for 2030 Roadmap (OECD, 2022; Rieckmann, 2022; UNESCO, 2024).

These competencies represent an educational shift beyond foundational scientific literacy, fostering students' capacity to integrate engaging with complex socio-environmental problems and to co-create sustainable solutions. Such integration supports the cultivation of not only disciplinary knowledge, but also the values, skills, and attitudes necessary for navigating and shaping a sustainable future. In doing so, the intervention directly contributes to the realization of SDGs, particularly Target 4.7, in quality education by offering an instructional innovation that integrates STEM and ESD principles to enhance students' scientific modelling skills. This target advocates education that promotes sustainable development, including the development of competencies needed to address global challenges. The intervention also aligns with Target 13.3, which calls for improved education and awareness of climate change mitigation and adaptation by providing students with contextually relevant, solution-oriented learning experiences grounded in local environmental issues. As students engage in these processes, they not only develop scientific modelling abilities but also internalize pro-environmental values and behaviors that reflect a scientific attitude toward sustainability. They also support basic scientific literacy, which includes the ability to understand scientific phenomena, construct explanations, and use evidence to inform reasoning; the intervention promotes transformative competencies as outlined in sustainability education frameworks (McNeill & Krajcik, 2008; Van Mil et al., 2013). These include systems, anticipatory, normative, collaboration, and self-efficacy. By incorporating STEM-Design Thinking and ESD principles, the learning design fosters students' capacity to act on sustainability challenges, empowering them to become proactive change agents in their communities.

Research Contributions

Practically, this study contributes by providing educators with a clear and structured instructional framework that progressively develops students' scientific modelling skills from initial observation and conceptualization to prototype creation and communication of scientifically supported solutions. Furthermore, the findings offer practical implications for teachers and educational professionals by demonstrating the feasibility and effectiveness of integrating STEM MDT in science education. This integration fosters motivation, engagement, and collaborative skills, preparing them to effectively analyze, model, and solve real-world sustainability problems (Ardianti et al., 2020). Additionally, empirical evidence from classroom implementation supports the STEM MDT approach, highlighting significant improvements in students' modeling skills and systems thinking competencies, thus equipping them to become responsible and capable future leaders in addressing global sustainability challenges.

These findings support previous research emphasizing the significance of incorporating STEM design thinking into science education focused on ESD to systematically improve students' skills (Hassan, 2023; He et al., 2023b; Hebebci & Usta, 2022). Evidence indicates that structured instructional frameworks, such as STEM MDT, can facilitate progressive learning from initial observation and conceptualization to the creation, testing, and communication of scientific modelling. This aligns with studies that demonstrate how developmentally suitable STEM interventions, including mobile applications and robotics kits, can foster essential modeling and computational thinking skills even in young learners (Kalogiannakis & Papadakis, 2020; Papadakis, 2019; Papadakis & Orfanakis, 2017; Yalçın, 2022). Furthermore, the current study is consistent with research in higher education that shows that interdisciplinary, sustainability-oriented STEM experiences enhance both the self-efficacy of preservice teachers and their understanding of complex environmental issues, particularly through design-based methodologies (Rico et al., 2021; Zhou et al., 2023). Our empirical findings extend this evidence to the secondary education context, demonstrating that STEM MDT can serve as a scalable and flexible approach to promote not only modeling skills but also systems thinking among students, which is essential for addressing real-world sustainability challenges (Demssie et al., 2023; Peretz, Dori, et al., 2023; York et al., 2019). By combining hands-on modeling with real-world ESD challenges, students actively engage in meaning-making, hypothesis testing, and refining their representations, an approach that aligns with the educational objectives outlined in the PISA 2025 science framework (OECD, 2025; Zhang et al., 2024). Therefore, the implementation of STEM MDT offers both pedagogical and epistemological connections between classroom learning and the competencies necessary to address future global challenges.

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This study makes several important contributions to STEM education. Validating a novel and effective pedagogical model for cultivating scientific modelling skills, demonstrating the added value of combining design thinking with science education, and providing practical strategies for integrating iterative, project-based learning into classroom practice. Moreover, it emphasizes the necessity of embedding ESD principles into STEM learning to foster critical and systems thinking (Sutinah et al., 2024; Tamir et al., 2023). In terms of practical implications, the STEM MDT intervention offers a replicable instructional framework that can enhance classroom engagement and promote student-centered activities (Motschnig & Holzinger, 2022). It also provides a valuable reference for teachers' professional development, particularly in training educators to facilitate modelling and design thinking processes in science lessons (Huang et al., 2022). From a curriculum perspective, this model supports the integration of interdisciplinary and sustainability-focused learning, aligned with current educational priorities (Kim et al., 2007). At the policy level, the findings support the need for the systemic encouragement of inquiry-based and design-oriented science education approaches, including the allocation of resources and training to scale such innovations (Cuevas et al., 2005). Future studies are encouraged to explore the applicability of this model in various scientific disciplines and school contexts, as well as to develop more sophisticated assessments of higher-order systems thinking and modelling competencies that may emerge from such interventions.

Innovative Pedagogical Framework for Advancing STEM Learning

Moreover, this study offers important contributions to the advancement of STEM education by validating a novel pedagogical framework, STEM MDT, which combines the epistemic practice of scientific modeling with the creative and iterative processes of design thinking. This integration not only facilitates students' understanding of scientific concepts but also fosters critical, systems-oriented reasoning that aligns with the contemporary frameworks of modeling-based and inquiry-based science education (Novak & Krajcik, 2019; Schwarz & White, 2005). In terms of practical implications, the STEM MDT intervention offers a replicable instructional framework that can enhance classroom engagement and promote student-centered activities (Motschnig-Pitrik & Holzinger, 2022). In terms of practical implications, STEM MDT provides a valuable foundation for teacher professional development, particularly in training educators to facilitate iterative modeling and design-oriented instruction in science classrooms (Huang et al., 2022). The model's emphasis on iterative construction, testing, and refinement reflects an authentic approach to science learning, bridging disciplinary knowledge with socio-environmental problem solving. From a curriculum development perspective, this model supports the integration of interdisciplinary, future-focused learning aligned with global education priorities and Sustainable Development Goals (Kim et al., 2007). At the policy level, the findings emphasize the need for systemic support to scale inquiry- and design-based science education, including adequate resourcing, curricular flexibility, and capacity-building initiatives (Cuevas et al., 2005). Future research should explore the transferability of this model across diverse scientific domains and educational contexts, as well as develop robust assessments to capture the emergence of higher-order modeling and sustainability competencies.

In addition to its contributions to STEM and ESD, this study offers valuable implications for science education by enhancing students' ability to interpret, construct, and critically evaluate visual data representation skills that are central to scientific literacy (L. Zhang et al., 2023). Through the STEM MDT framework, students engage in iterative modeling processes that require them to analyze and communicate information using visual tools, such as graphs, charts, and conceptual diagrams, thus supporting the development of graphical perception and data interpretation competencies (Cleveland & McGill, 1985; Lynch & Woolgar, 1990). This aligns with the increasing demand for visual data literacy in science education, particularly in ensuring that visual elements such as color maps are scientifically valid, accessible, and free from distortion, especially for students with color vision deficiencies (Crameri et al., 2020). Furthermore, by integrating modeling tasks within a structured and contextually meaningful instructional design, this study addressed the key factors influencing students' understanding of visual representations, such as cognitive load and prior knowledge (Cook, 2006). It also reinforces the idea that, while alternative forms of data representation can enhance conceptual understanding, they must be critically designed to avoid misinterpretation (Eisner, 1997). Therefore, STEM MDT contributes to science education not only by improving modeling skills but also by cultivating students' data literacy, visual reasoning, and critical thinking core competencies required to navigate complex scientific and real-world information.

Finally, it was established that the implementation of STEM MDT significantly boosts students' scientific modeling skills. Studies that compare the experimental group using the STEM MDT learning model with the control group implementing STEM PjBL indicate that incorporating ESD topics into the STEM MDT approach is more effective in

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improving students' scientific modeling skills. These findings reinforce those of previous studies, although some research has also reported that STEM learning based on design thinking generally has a positive impact on scientific modeling activities within the engineering design process (Atman et al., 2007). Additionally, integrating ESD into project-based learning contexts that relate to real-world scenarios offers students considerable motivational benefits. Intricate and diverse ESD topics, such as climate change, foster students' curiosity and motivate them to explore important issues from multiple perspectives. This approach inspires students to actively collect additional information, analyze the accuracy and relevance of the data, and construct persuasive arguments to solve problems through scientific modeling. Thus, this learning model not only enhances students' interest in learning but also prepares them to become responsible individuals capable of addressing and solving real-life problems sustainably.

Conclusions and Implications

Through rigorous data analysis and interpretation, this study provides robust empirical evidence that the STEM MDT model is more effective than STEM PjBL in enhancing students' scientific modeling skills. When examining the experimental and control groups separately, both groups showed improvements in their scientific modeling skills. However, the STEM MDT, which integrates ESD issues at the real world application level, contributes more positively to students' scientific modeling skills than conventional project-based STEM learning. The effects of this integration are apparent in the enhancement of students' capabilities to recognize issues, propose different solutions, and effectively execute those solutions in the context of ESD. This indicates that innovation in modeling-based learning and ESD is essential in science education to equip students with the various essential skills needed to tackle complex issues in the future and prepare them for PISA assessments.

The implications of this study indicate that the STEM MDT model can be a valuable instructional innovation in science education, particularly when grounded in real-world applications and sustainability-oriented learning. By embedding the principles of ESD, this approach fosters students' critical thinking, analytical reasoning, and synthesis skills, which are necessary to address global challenges and adapt to dynamic social changes. Therefore, educators and policymakers should consider adopting this model to promote adaptive, inquiry-based, and future-oriented science learning. Moreover, while the study demonstrated encouraging outcomes, it is important to interpret the results with caution. Specifically, the relatively low person reliability reported in the Rasch analysis suggests potential limitations to estimating individual students' ability levels with high precision. This may have affected the robustness of the conclusions drawn at the individual level. However, it is noteworthy that the instrument exhibited high item reliability and item separation indices, indicating that it was effective in distinguishing item difficulty and was suitable for making valid inferences at the group level. Future research may refine the assessment tools or employ additional measurements to enhance the reliability of individual level estimate.

Limitations and Future Research

This study provides significant contributions to advancing science education through the integration of STEM-MDT and ESD; however, several limitations must be acknowledged. First, the relatively small and localized sample size restricts the generalizability of the findings to larger populations. Second, the intervention was carried out over a short period of four weeks, which may not fully capture the long-term impact of the STEM MDT. Third, the study was conducted within a specific cultural and educational context, which can influence how the model is received and implemented in different regions or school systems. Future research is recommended to test the applicability of the STEM MDT model across diverse educational settings, extend the duration of the intervention, and incorporate more varied assessment methods to evaluate long-term learning outcomes and transferability. Fourth, while the Rasch analysis indicated acceptable item reliability and separation, the person reliability index was relatively low. This suggests that the instrument may have limited sensitivity in distinguishing students' abilities at the individual level. Therefore, caution is warranted when interpreting findings related to individual performance, as the measurement precision may be more robust at the group level than at the individual level. Future studies should consider enhancing the instrument's person reliability by increasing the number of items or improving item targeting to better capture individual differences.

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Declaration of Interest

The authors declare no competing interest.

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